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A PASSIVELY CONTROLLED APPENDAGE DEPLOYMENT SYSTEM FOR THE SAN MARCO D/L SPACECRAFT

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Abstract

The need for adding deployable inertia booms to the San Marco D/L spacecraft developed from a critical spin stability and weight margin problem which became apparent when the flight spacecraft was well into the final integration phase. Available options reduced to either despin of the system followed by deployment at reduced speed or deployment at the final stage spin rate of approximately 115 rpm. Spinning deployment involves transition to a lower energy state which the deployment mechanism must accommodate. The configuration dictated that the add-on boom units attach to existing pitch and yaw axis interfaces and fold back within a restrictive heat shield envelope.

As a single axis hinge design could not accommodate high-speed deployment, concepts where the boom hinge assembly can also rotate about the spacecraft radial pitch or yaw axis were studied in depth. This paper describes the analytical simulation of deployment dynamics of these 2-axis concepts as well as the evolution of practical designs for the add-on boom units.

With the boom free to swing back in response to Coriolis forces as well as outwards in response to centrifugal forces, the kinematics of motion are complex but admit the possibility of absorbing deployment energy in frictional or other damping devices about the radial axis, where large amplitude motions can occur and where the design envelope allows more available volume.

An acceptable range can be defined for frictional damping for any given spin rate. Inadequate damping allows boom motions which strike the spacecraft; excessive damping may cause the boom to swing out and latch with damaging violence. The acceptable range is a design parameter and must accommodate spin rate tolerance and also the tolerance and repeatability of the damping mechanisms.

Introduction

The San Marco D/L is the latest of a series of spacecraft in an international cooperative program involving NASA and the Italian Centro Ricerce Aerospaziali (CRA). The spacecraft is to be launched by a Scout rocket from a site off the east coast of Africa with the primary mission being to study the equatorial region upper atmosphere. The spacecraft is larger than its predecessors and similar in general configuration, having a

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quasi-spherical lightweight outer shell coupled via load sensors to a rigid and comparatively massive central body to evaluate atmospheric drag. It contains other scientific instruments, is spin stabilized, and has 4 wire antennae which deploy radially, plus two "STEM" type antennae which extend along the spin axis.

It will also have deployable inertia booms which are needed because of a critical spin stability and weight margin problem which became apparent when the flight spacecraft was well into the final integration phase. The evolution of this problem and the development of the add-on boom units intended to solve it are the subjects of this paper.

All San Marco spacecraft needed a so-called triaxial mass balance to accommodate the primary drag balance experiment. The mass centers of the inner body and outer shell must both be essentially coincident with each other and with the geometric center and the center of pressure of the outer shell. Also, the products of inertia about all 3 reference axes of the drag balance experiment, and especially about the spacecraft spin axis, must be minimized. Reference 1 discusses the subject of triaxial balancing. Spin balance of the spacecraft about the spin axis of the final stage booster is a concurrent requirement, complicated by the logistic sequence that the spacecraft is balanced in Rome, Italy, the booster is balanced in Wallops Island, Virginia, and they are never mated and aligned until final assembly at the equatorial launch site, where balance of the final assembly cannot be done.

There is also the basic spin stability requirement that the spin axis be a major principal axis with moment of inertia greater than pitch or yaw axes. In this case, an extra inertia ratio margin was needed to accommodate the spin axis antenna extension, but some offsetting margin reduction results from radial wire antenna deployment. The mission sequence is spin up, booster ignition, burn out, separation, coast, radial boom deployment (in stages) and finally spin axis boom extension, with spin stability needed throughout the sequence.

Evolution of the Problem

As the flight spacecraft integration became relatively complete, weight and moment of inertia measurements were made with disconcerting results. The projected weight was more than expected and allowed little margin below maximum vehicle capability for the planned orbit. Also, the projected moment of inertia ratio was unfavorable and could not be corrected by adding mass within the weight margin or within the outer shell, as the inner body was a densely packed configuration. Furthermore, mass moment checks showed considerable static unbalance about all 3 axes and dynamic spin balance about any axis had not yet been done.

It was felt on the basis of earlier San Marco experience that up to 4 percent of total spacecraft weight should be budgeted for triaxial balancing and even with an inertially favorable moment of inertia ratio this would have made the weight margin very critical.

Available options were considered, and, other than unacceptable expedients such as removing experiments from the spacecraft, reduced to developing add-n deployable inertia boom units attached to the existing pitch and yaw axis handling fixture interfaces. These 4 booms would fold back within the restrictive heat shield envelope and might require a preliminary yo-yo despin device in order to survive deployment.

This would correct the inertia ratio problem. The balance problem was to be reconsidered after making spin balance measurements about all 3 axes so that the extent to which necessary corrections could be vectorially combined within the outer shell envelope could be evaluated.

Thinking on boom designs rapidly polarized to either a simple, single hinge axis design which would need a yo-yo device, or more sophisticated ideas with multiple hinge axis degrees of freedom, frictional energy absorbing devices, and complex deployment dynamics which might not need a yo-yo or which would at least survive if the yo-yo did not work. It was decided to proceed with both concepts in parallel and with detailed design of the "simple boom," pending better resolution of the actual weight margin after balancing.

After more spacecraft integration, revised weight and moment of inertia measurements and the first spin balance measurements were performed. Various strategies for unbalance correction were tried with due consideration for practical limitations on where the structure allowed weights to be located. The most obvious correction considering mass moment and product of inertia components separately and correcting by adding weights at structurally convenient locations, needed about 9 Kg. Vector combination of these components reduced the weight required to 6.2 Kg at the expense of more inconvenient positioning of correction weights.

Meanwhile, an additional constraint was imposed on the boom design. It had been determined that the degree of shading that the deployed booms would cause to the solar cell panels was acceptable. However, the radial deployed position of 2 of the booms would violate the required field of view of a major onboard experiment, and it was required that the booms be skewed 7 degrees in the pitch/yaw plane. This could be done, but added some weight to the boom structure due to the need for a wedge shaped attachment flange, and necessitated the development of new spacecraft handling devices and procedures.

The question of spacecraft handling logistics and boom alignment merits discussion as a separate but related problem area. The San Marco is balanced using stub arbors attached to the booster interface and to a dummy forward interface, for the spin axis, or to accurate orthogonal holes in the structure for the pitch and yaw axes. These pitch and yaw interface holes have two other functions. They are used to screw in radial lifting handle bars for spacecraft lifting and rotation. They are also used to attach the add-on inertia boom units or rather the attachment flanges for the booms.

Figure 1 shows a sectional view of the boom attachment to the spacecraft.

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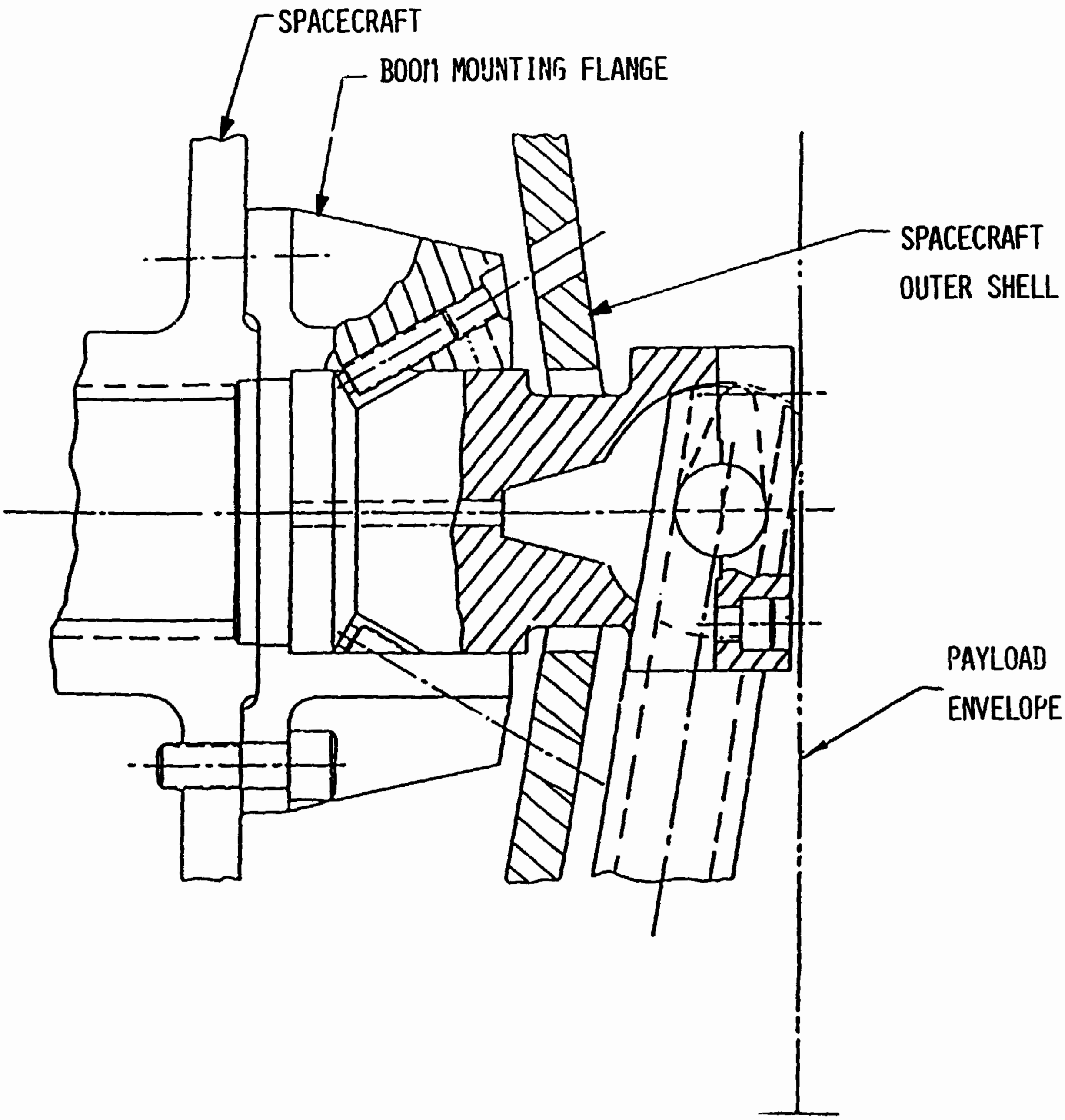

Figure 1. Boom Attachment to Spacecraft

Figures 2, 3, and 4 show other features of the boom system. The flange which is the actual interface to the spacecraft is wedge-shaped and skews the boom 7 degrees. Before the flanges are installed, the radial threaded holes in the spacecraft structural frame are used to attach and accurately align the balancing arbors and also to insert radial handles for spacecraft lifting and pitch rotation. The boom flanges are to be installed and aligned after balancing, but there is a need for handling about a lateral axis after the boom flanges are installed and aligned and the original handles cannot be used because of the 7 degree skew, so new handles are needed, made with a 7 degree skew and to fit into the sockets for the boom hubs. The boom hubs and booms can be removed from the flange sockets and are aligned and secured by angled set screws accessible through holes in the spacecraft outer shell. Thus, the booms can and must be assembled and/or removed with the outer shell in place since the outer hubs are larger than the holes in the outer shell.

The spacecraft balancing requirements make it necessary that the deployed position of the booms be controlled as accurately as possible and be repeatable after several test deployments and the final flight deployment. A limit of 3 mm deviation of boom tip location from nominal, in any direction, was established as the practical limit of feasible manufacturing tolerance control for slender booms almost a meter long. As the desired control of residual unbalance implied no more than 1 mm tip location deviation, it is necessary to accurately measure and/or control the tip alignment to this level of accuracy as a mass property status input. Tip alignment control is to be by shims under the boom attachment flanges; therefore, the flanges should not be removed after alignment. Boom deflection due to gravity is to be considered or negated during boom tip alignment operations. The boom tip location requirements, as well as the need for minimum boom weight, were important design factors for the booms.

Analysis of Boom Deployment Dynamics

The configuration dictated that the inertia booms be folded down to 9 degrees past vertical, skewed back 15 degrees to clear the spacecraft umbilical tunnel, and that the deployed booms be in the pitch-yaw plane but skewed 7 degrees from radial in the direction of spin. All booms were to be 0.836 m long, with a tip mass to be as required for mass property control, but not expected to exceed 1 Kg. The pre-deployment spin rate would be approximately 115 rpm without yo-yo despin or 38 rpm if a yo-vo were used. In either event, deployment would reduce the spin rate by about 10 percent and impose Coriolis forces during deployment as well as high stresses at lock-in to deployed position.

Spinning deployment involves transition to a lower energy state, with conservation of angular momentum, and as it became apparent that a single hinge design could not withstand high-speed deployment, concepts where the boom hinge assembly could also rotate about another axis orthogonal to the hinge axis were studied in depth. This second axis as well as the hinge axis would have to be skewed 7 degrees from the spacecraft radial axis to accommodate deployed position requirements.

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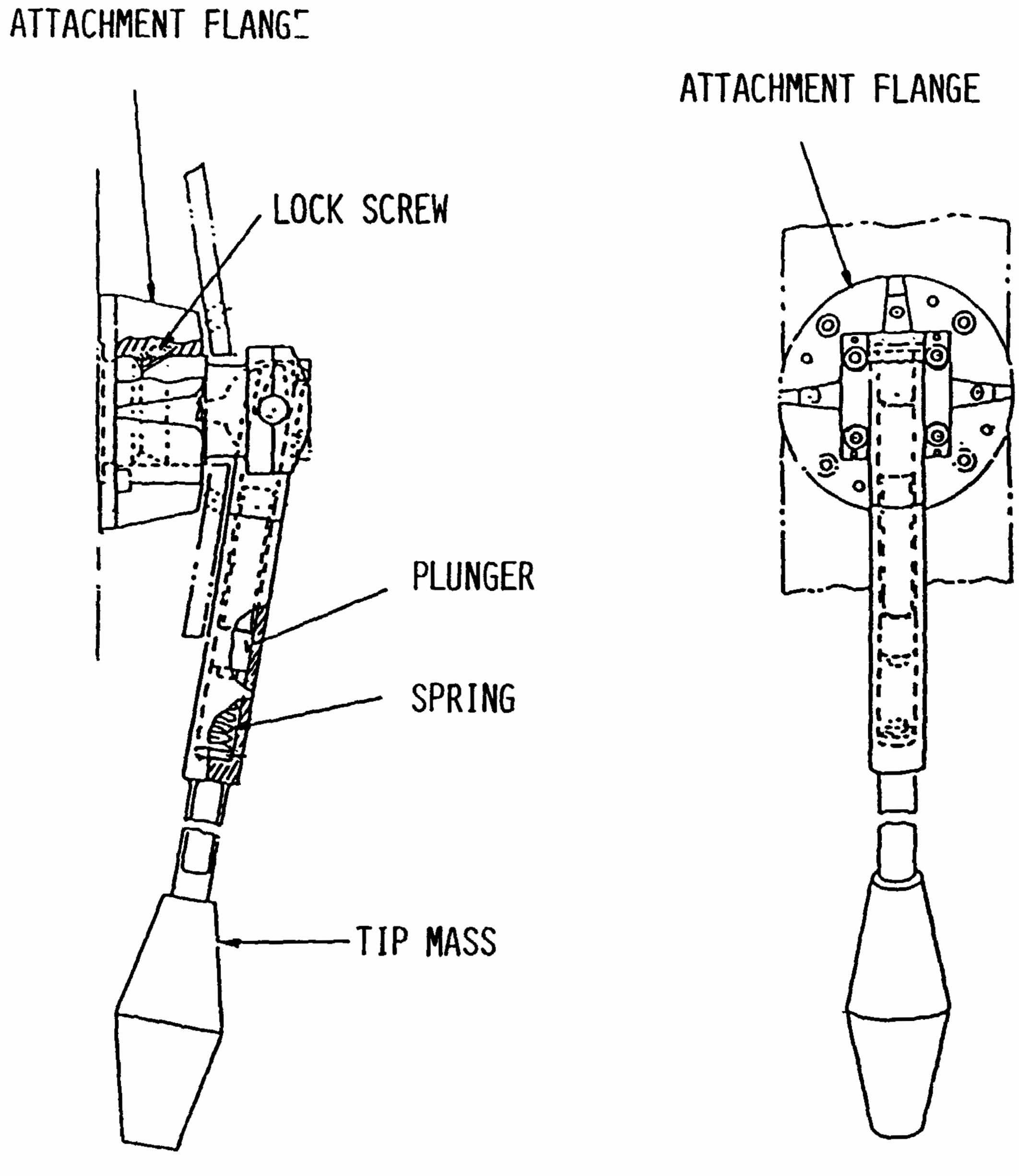

Figure 2. Inertia Boom Assembly

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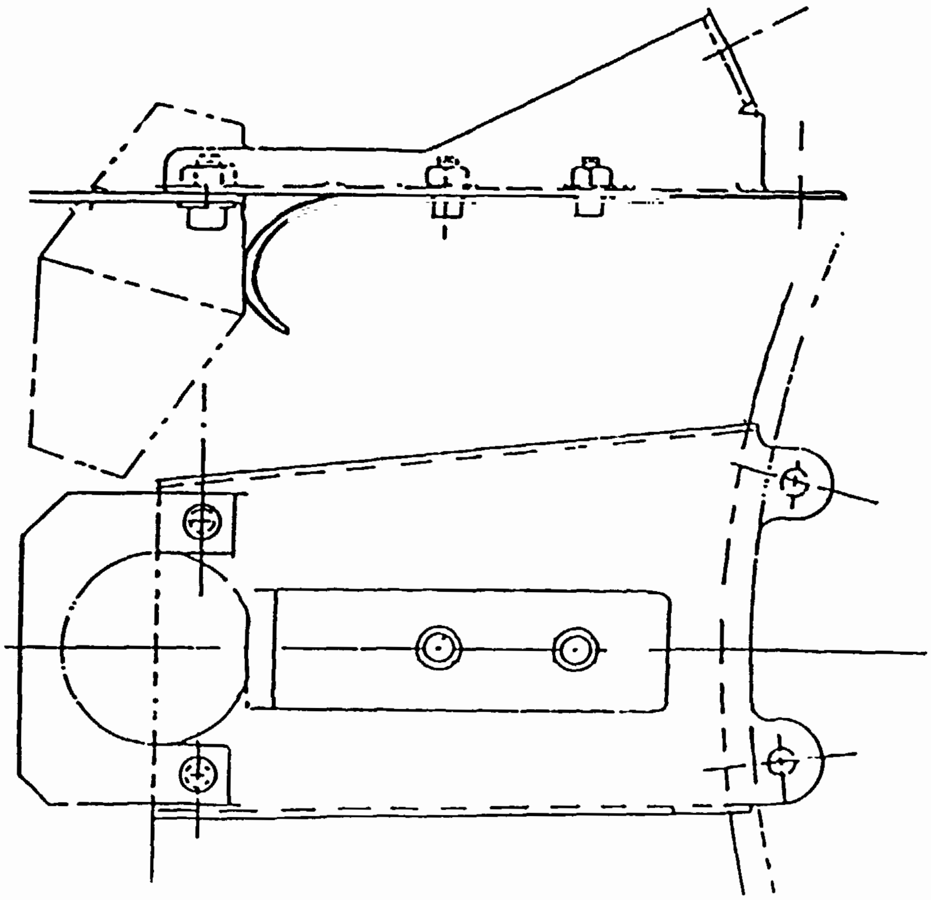

Figure 3. Tip Mass Restraint Bracket

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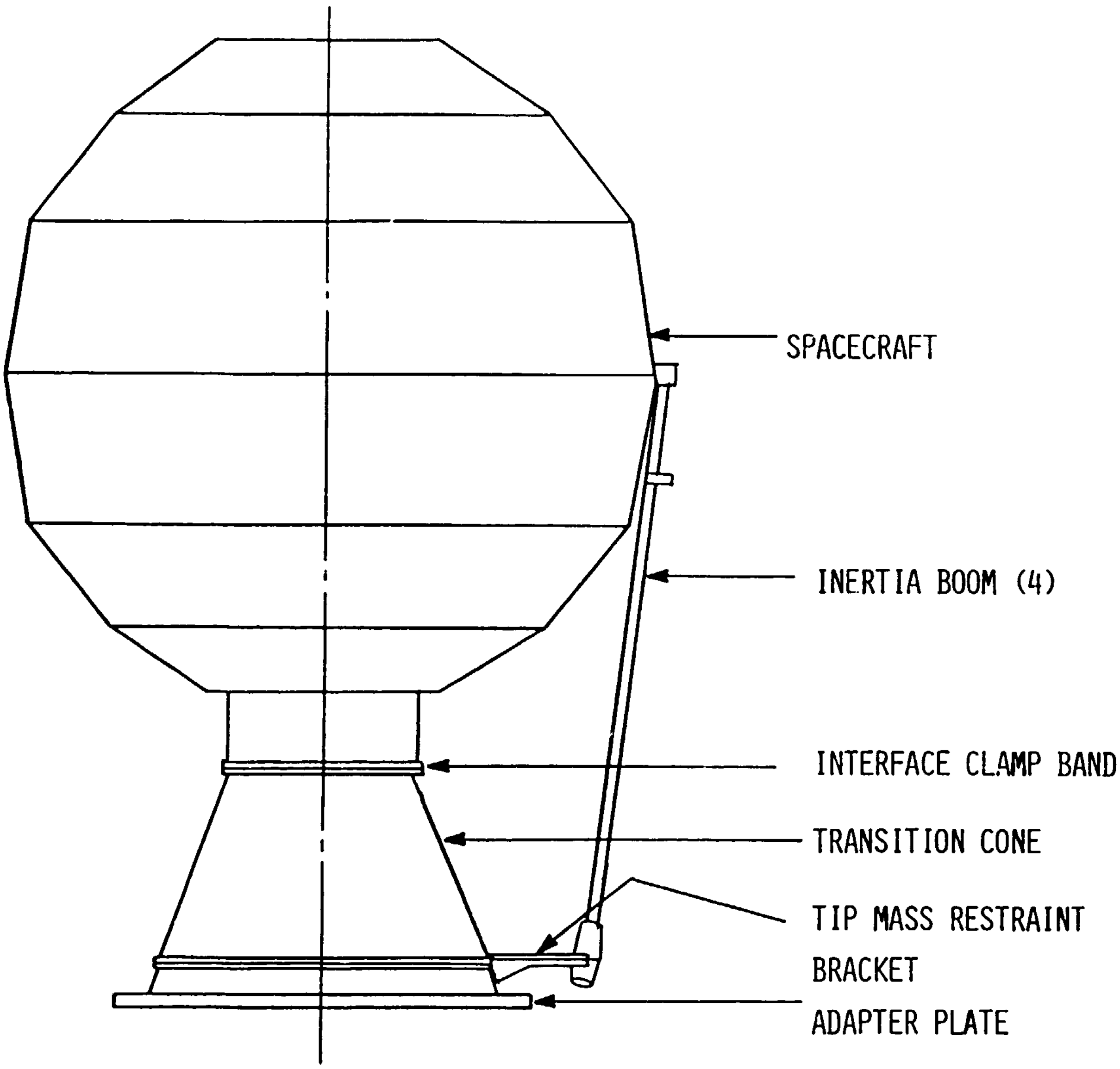

Figure 4. Assembly for Boom Testing

With this second degree of angular freedom, the boom would be free to swing back subject to Coriolis forces as well as outward in response to centrifugal forces. The dynamics of the resulting boom motion during deployment are complex and admit the possibility of absorbing deployment energy in frictional or other damping devices about the axes of both degrees of angular freedom. The second axis, orthogonal to the hinge axis, offered the potential for large amplitude motion with consequent high energy dissipation as well as more available volume for damping devices within the constraints of the design envelope.

Computer Simulation of the 2-Axis Boom Deployment Concept

Computer simulation programs used to study high-speed San Marco boom deployment dynamics have evolved in both fidelity and capability. The understanding of the problem achieved via these simulations has lead to the 2-axis boom deployment concept.

In order to avoid deriving and computer coding equations of motion, the general purpose computer programs N-BOD2 (Reference 2) and DISCOS (Reference 3) were utilized. These programs allow the spacecraft to be modeled as a central rigid body with 4 rigid or flexible appendages. The programs automatically set up the complete set of nonlinear equations of motion taking into account all gyrodynamic interaction effects with no small angle assumptions used. Our task was to define the deployment mechanism in a form compatible with simulation program needs and limitations. Several models for this mechanism were developed. Each new mechanism model added a degree of simulation fidelity and capability not previously present.

The initial 2-axis boom deployment concept investigated consisted of a conical plunger latch with a stiff prestressed spring acting as a boom deployment actuator. It was reasoned that if the prestress level in the spring could be set high enough, adverse Coriolis effects could be overcome and latching would be achieved. The N-BOD2 model for this concept consisted of a central rigid body with 4 identical point connected rigid booms. Each boom had 2 degrees of relative freedom and was symmetrically placed in a plane normal to the spin axis around the spacecraft perimeter. The latching mechanism was modeled as a constant magnitude torque always acting in the direction which aids deployment. The simulation was initialized with a spin rate of 115 rpm and with all 4 booms stowed parallel to the spin axis. These were simultaneously released with zero initial velocity at time zero. The only nongyroscopic load on the system was that associated with the actuator spring in the latching mechanism. Computer simulations revealed that, to overcome Coriolis effects and to insure that the booms would not swing back and strike the spacecraft, spring prestress had to be set at a level beyond that which could be obtained in the space available with obtainable materials. It was further determined that if latching occured before a significant amount of system energy could be dissipated, the booms had the potential to either break off or be permanently deformed.

In addition to uncovering flaws in initial design concepts, these N-BOD2

simulations provided us with a clearer understanding of boom deployment dynamics. Most importantly, it was noted that the interaction of centrifugal and Coriolis effects tended to produce a resultant boom motion which, to an observer on the spacecraft, appeared as approximate crescent-shaped patterns traced by each boom tip.

Initially, the crescent radius is large while the boom oscillates near the spacecraft, then as the system dissipates energy through various damping mechanisms crescent radius reduces, and the boom approaches the fully deployed state. From this observation, it was reasoned that if the deployment mechanism was free to rotate about the axis defined by the fully deployed boom, the back and forth crescent shaped swinging motion could, so to say, be captured. Then if a braking mechanism could be designed to inhibit this rotational motion, significant amounts of energy could be dissipated through damping prior to latching. The net result would be less violent boom motion with acceptable latching loads. The 2-axis boom deployment concept, discussed herein, is the outgrowth of these initial ideas refined to accommodate system design and scheduling constraints.

The braking mechanism envisioned may be conceptualized as a brake of the friction disc stack type similar to a pedal operated bicycle brake but dimensionally adjusted to fit into available space. By presetting brake pressure before launch, the amount of damping desired could be controlled. Several simulation runs were made to determine at what level the braking pressure should be set at to minimize latching loads, resultant boom elastic deformation, and hinge constraint loads. As a by-product of the numerous runs made, a measure of parameter sensitivity was also determined; crude settings were found to be adequate.

Computer simulation of this mechanism design was achieved via use of the computer program DISCOS. DISCOS provided the ability to extend modeling capability to include the effects of appendage flexibility without introducing any small angle or small displacement assumptions. Boom flexibility was considered to be a parameter which could not be ignored. It was reasoned that the interplay between the tip mass attempting to dominate boom tip deployment dynamics and the mechanism attempting to dominate boom root deployment dynamics would result in significant elastic deformation; it did.

The DISCOS model for this series of simulation programs consisted of a central rigid body with 4 identical elastic beams symmetrically located around the perimeter. Each beam had both distributed mass and a tip mass. Three degrees of elastic freedom were assumed: 2 bending modes, 1 for each orthogonal bending direction, and 1 torsional mode. The DISCOS input specification for the booms consisted of a lumped parameter model. It defined both mass distribution and modal displacement. First clamped-free bending and first torsional modes of oscillation were used. Stiffness was defined by providing modal frequencies. All runs assumed that both bending frequencies were equal, this implied booms with symmetric cross section. The torsional frequency was varied for a few runs to determine if large amplitude bending could induce significant torsional response; it did not. Modal damping could and was also included. It was included primarily to

get rid of the high frequency transient response which masked steady state performance characteristics. The damping values used were consistent with what one would expect to observe for large amplitude oscillations.

The 2-axis deployment mechanism was modeled as a 2-axis gimbal with appropriate damping models specified about each axis. One gimbal axis was defined parallel to the fully deployed boom axis; motion about this axis is intentionally damped by the braking mechanism previously discussed. The other gimbal axis, that is the boom deployment axis, was fixed in the boom normal to its longitudinal axis. Motion about this axis was subject to dry friction taken to be proportional to the constraint torque acting about the axis normal to both gimbal axes. A Dahl friction model was actually used for the description of damping about both axes; that is, below a pre-defined breakaway torque the Dahl friction model is a simple linear spring dashpot. Beyond this point dry friction associated with sliding takes place. This type of friction model is extensively used to model friction associated with systems containing ball or roller bearings. It is also appropriate for the 2-axis boom deployment mechanism.

As in the earlier series of N-BOD2 simulation runs, initial spin rate was set at 115 rpm with booms released from their stowed position with zero initial velocity at time zero. System parameters were varied from run to run in an attempt to find the value of breakaway torque for the braking mechanism which would minimize constraint loads on the gimbal, boom elastic deformation, and the potential of the boom swinging back onto the spacecraft. The net conclusions reached from this series of runs was that it was possible to reduce constraint loads and the potential of boom swing back to acceptable levels; however, elastic deformation could not be reduced to the point where no permanent deformation could be assured.

Further simulation runs revealed that there was another flaw in initial design concepts. The attempt to minimize boom plus tip mass weight lead to the placement of as much extra mass as possible in the tip, thus, weakening the boom. This, so to say, caused a conflict between the tip mass's attempt to dominate boom tip deployment and the mechanism's attempt to dominate boom root deployment. The relatively weak boom effectively allowed both ends to act independently with the boom accommodating via large amplitude deformation. Making use of this new understanding, runs were made with no tip mass and increased boom mass per unit length. The net result was that the mechanism at the boom root dominated total boom deployment and overall performance was acceptable.

Other system parameters were also varied during the course of the study, such as the friction coefficient associated with motion about the deployment axis and initial release position. These runs lead to intuitively obvious conclusions, increased friction in the deployment hinge helps while release from a position other than parallel to the spin axis has no significant effect on overall deployment performance.

Some typical computer output plots are appended as Figures 5, 6, 7, 8, and 9 and are annotated as to significance and interpretation. The end products of a large number of computer runs were some limiting design

criteria and a much better understanding of deployment dynamics.

Limiting cases are of interest and contribute to understanding the situation. With no friction, angular oscillations continue repetitively without damping, and the boom would never latch. On the other hand, if breakaway friction torque exceeds the maximum induced Coriolis torque then there is no sliding about the friction torque axis, and again there is no energy dissipation. This case actually reverts to the simple single hinge boom design--the boom swings out about the hinge axis, and all the deployment energy has to be dissipated at latch-in except for any dissipation due to hinge axis friction.

These considerations led to a design option which is being considered at the time of writing. The booms would be designed to slip about the Coriolis torque axis at a relatively high breakaway torque level, based on an initial spin rate of about 115 rpm. However, the flight system would have a yo-yo designed to reduce spin rate to 38 rpm. If the yo-yo worked, the booms would deploy as a simple single hinge boom, as the Coriolis torque would not be high enough to cause slipping. The booms would be designed to deploy as single hinge booms, at 38 rpm. However, if the yo-yo failed to despin the system, deployment would occur at 115 rpm, Coriolis torques will cause slipping and energy dissipation, and the booms would have at least an enhanced chance of survival for this yo-yo failure mode.

Scale Model Studies

A 1/9 scale dynamic model was built to demonstrate and evaluate the 2-axis boom deployment concept. It had 2 opposed booms with freedom to rotate about the hinge axis and a radial axis, with adjustable torque friction brakes on the radial (Coriolis) axis. There was no deployed position latch, but there was a device to spin up and hold the booms in a folded up position and then release them to deploy.

The model was spun up and deployed at several speeds and torque brake settings, including essentially no friction and friction high enough to stop Coriolis slipping so that the booms deployed as single hinge axis booms. High-speed movies were made of some of these model deployments, and review of them provided an interesting confirmation of the general results of the analytical studies.

With no resistance to Coriolis slipping, the booms perform wild gyrations, including whipping back as far as the hinges allow, confirming that collisions with the spacecraft envelope could occur with inadequate damping. With high friction so that there is no Coriolis slipping, the booms swing out rapidly about a single hinge axis, and flap repetitively, since the model has no latches. With intermediate friction, the booms reach a radially deployed position without excessive gyrations, but the model did not allow accurate frictional matching of the 2 opposed booms so their motions were not in phase. Furthermore, the model had rather stiff booms; and, hence, it was not possible to demonstrate adverse elastic deformation predictions.

Boom Latching Considerations

The inertia booms have to latch into an accurately controlled deployed location because of the spacecraft mass property requirements. However, the latch also has to accommodate high levels of energy at latch in. In other words, the booms latch in fast and hard.

An acute angle conical plunger latch, with a stiff spring actuator, meets the needs for accurate positioning and rapid actuation, though imposed loads are high, on both the latch and the boom.

From the point of view of high-speed deployment capability, the type of detent device which can swing over center and dissipate energy in damped oscillations was attractive. However, it did not seem feasible to design a device of this type with acceptable positioning accuracy or to fit within the available design envelope or to attempt such a design within the developmental time span dictated by the mission schedule.

Current Status of Boom Deployment

The latching consideration and other aspects of the subject system exemplify a dilemma which is commom in aerospace mechanism design. We had to come up, very quickly, with a design which could be retrofitted within a mandated schedule and which would do the job acceptably and reliably. We could not afford the luxury of searching for a solution which may have been optimum and perfect, but too late. We also had to start design and make development decisions before all the design parameters were known or understood. The current boom design status is shown in the appended Figures 1 through 4.

Figure 1 shows the angled boom attachment flange with the boom hub inserted into a socket and secured with angled set screws after rotating about the hub axis to align the folded boom tips into the booster cradles. The booms are folded down about 9 degrees past vertical as well as angled back 15 degrees to avoid the spacecraft umbilical tunnel. Thus, the cradles are oriented 15 degrees from the boom flange mounting axes. When the spacecraft separates from the booster, the booms are pulled up out of the cradles and are then free to deploy. The assembly is spinning at separation, at 38 rpm if the yo-yo works, or at 115 rpm if it does not. When the boom reaches a deployed position, a spring-loaded conical plunger is pushed into a socket in the hub, latching the boom into an accurately aligned deployed position. If excessively high Coriolis torques are developed due to high spin rate, the hub is potentially free to slip, depending on the set screw torque, dissipating some energy. This slipping would not affect the deployed boom position but only its angular orientation about the hub axis.

The boom has a tubular inner section, containing the plunger and spring, and an outer section with a wide flat cross section (0.75 inches wide and 0.39 inches deep). The conical tip is to engage and separate from the cradle. The boom is titanium and designed as a distributed mass unit to match the expected nominal inertia control requirements. However, it has a

series of pilot holes in the outer section, to enlarge as lightening holes or to accommodate mounting small slugs of high density tungsten alloy, as may be required for final balance and/or inertia trim.

Update of the Current Status of Boom Development

The foregoing has described the subject ongoing development up to the time of writing. An appropriate updating supplement will be available at the 18th Aerospace Mechanisms Symposium.

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3. Frisch, H. P., "A Vector-Dyadic Development of the Equations of Motion for n-Coupled Flexible Bodies and Point Masses," NASA Tech. Note TN D-8047, 1975. (Program code available COSMIC, University of Georgia, Athens, Georgia, Program GSC-12346.)

APPENDIX

COMPUTER SIMULATION PLOTS

The following series of figures illustrate system dynamics of the San Marco spacecraft from boom release through latch in.

Figure 5 shows the total energy of the spacecraft system. From 0.0 seconds until 0.47 seconds, energy decrease is attributed to frictional damping in the deployment mechanism. Energy increases between 0.47 and 0.54 seconds when the prestressed spring in the conical plunger snaps the boom into its fully deployed position. After that time, energy loss is from the viscous damping associated with boom bending.

Figure 6 is the spin rate of the main body. It begins at 38 rpm (3.98 rad/sec) and decreases as the booms deploy. At full deployment (0.54 sec), its speed varies between steady state and slightly above steady state, as the booms' motion settles.

In Figure 7, a boom's initial deployment angle is 90 degrees. As the booms are released, the angle reduces to zero degrees which is its fully deployed position.

Figures 8 and 9 show constraint torque at the boom's hinge. In Figure 8, the torque normal to the deployment plane is shown. It is zero until latch in occurs. Thereafter, the deployment mechanism resists motion, and a constraint torque is created.

Coriolis effects cause torques in the deployment plane (Figure 9). Upon boom release, constraint torques are immediately apparent as the deployment mechanism resists motion normal to the deployment plane.

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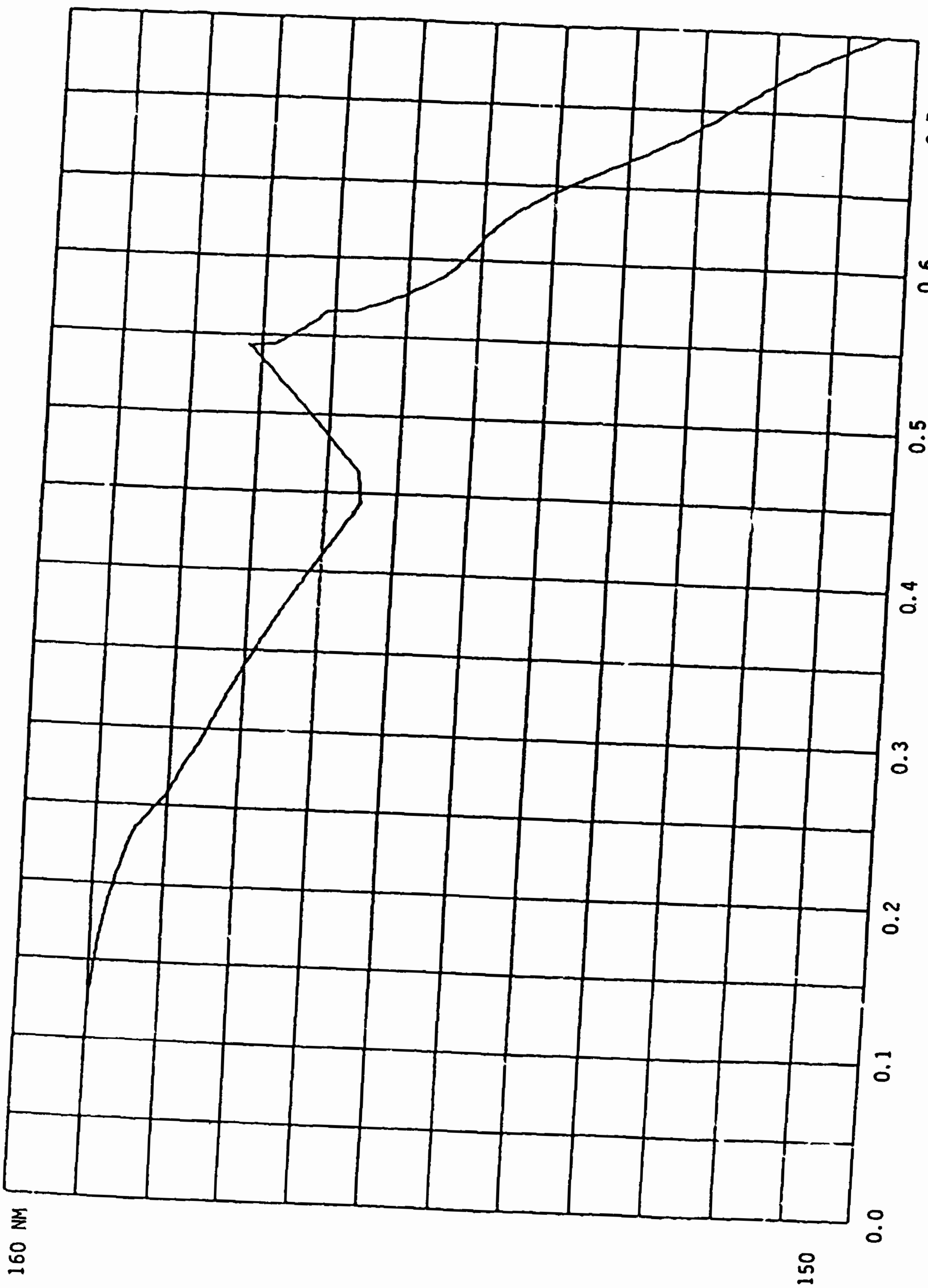

Figure 5. Total System Energy

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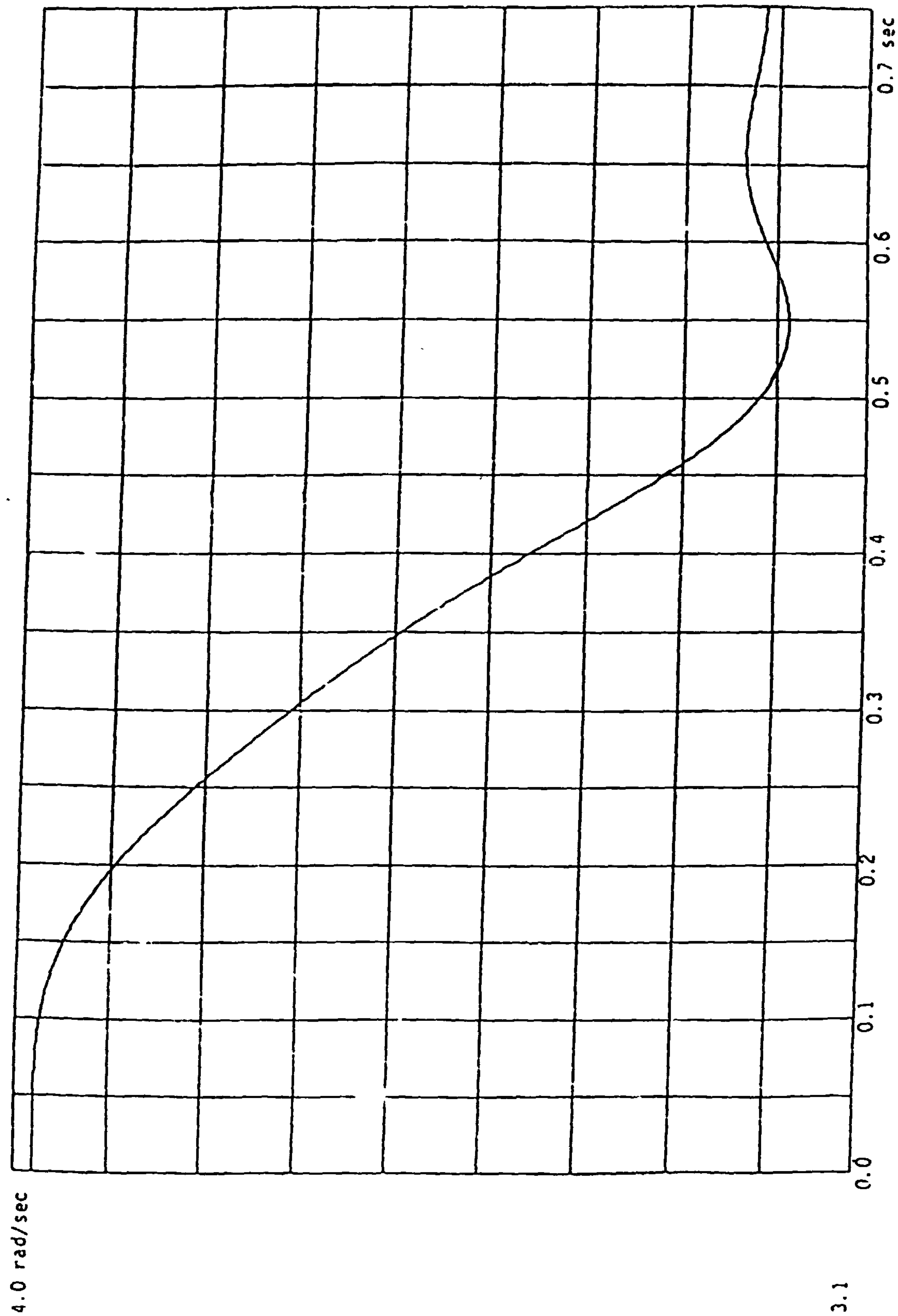

Figure 6. Spin Rate

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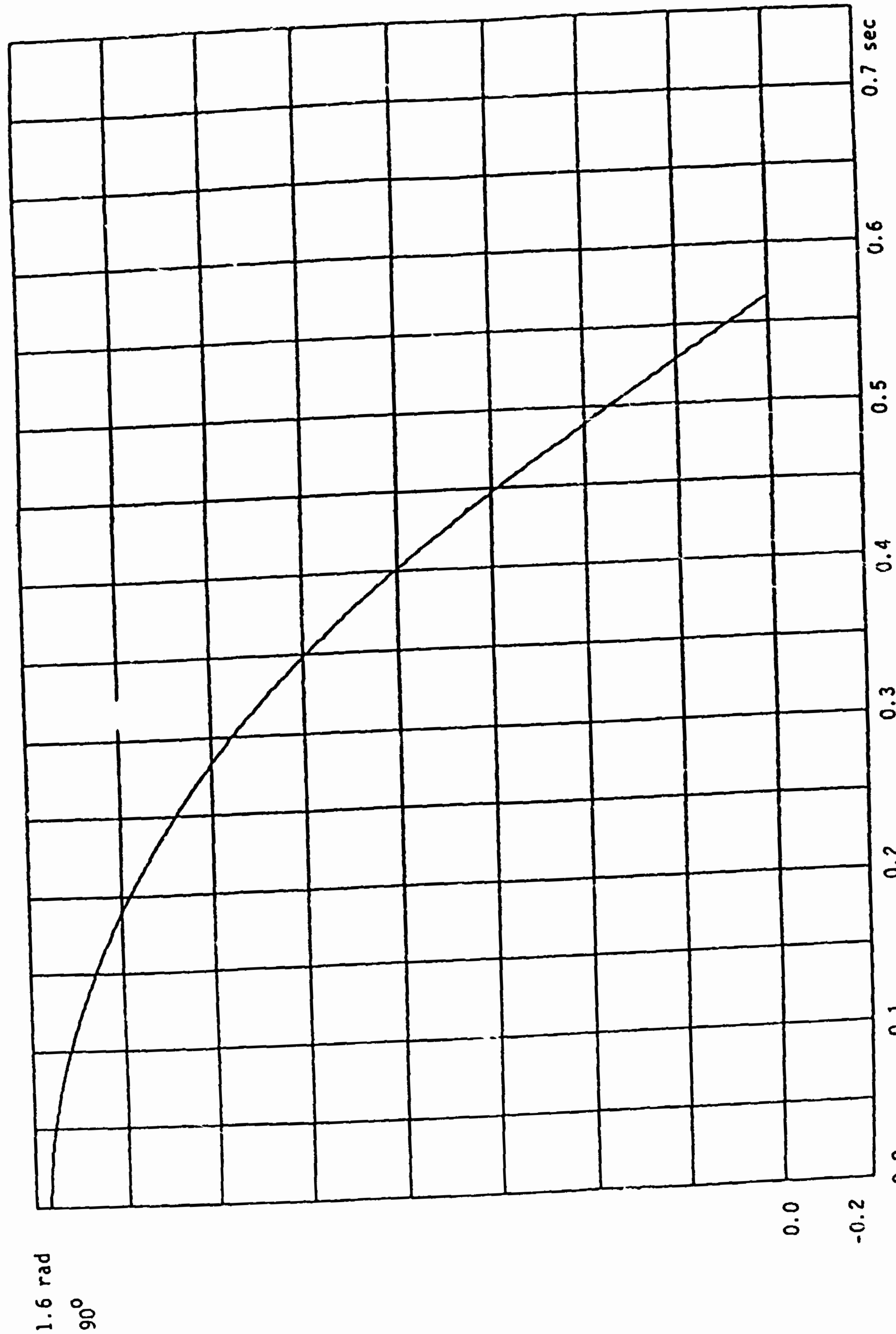

Figure 7. Boom Deployment Angle

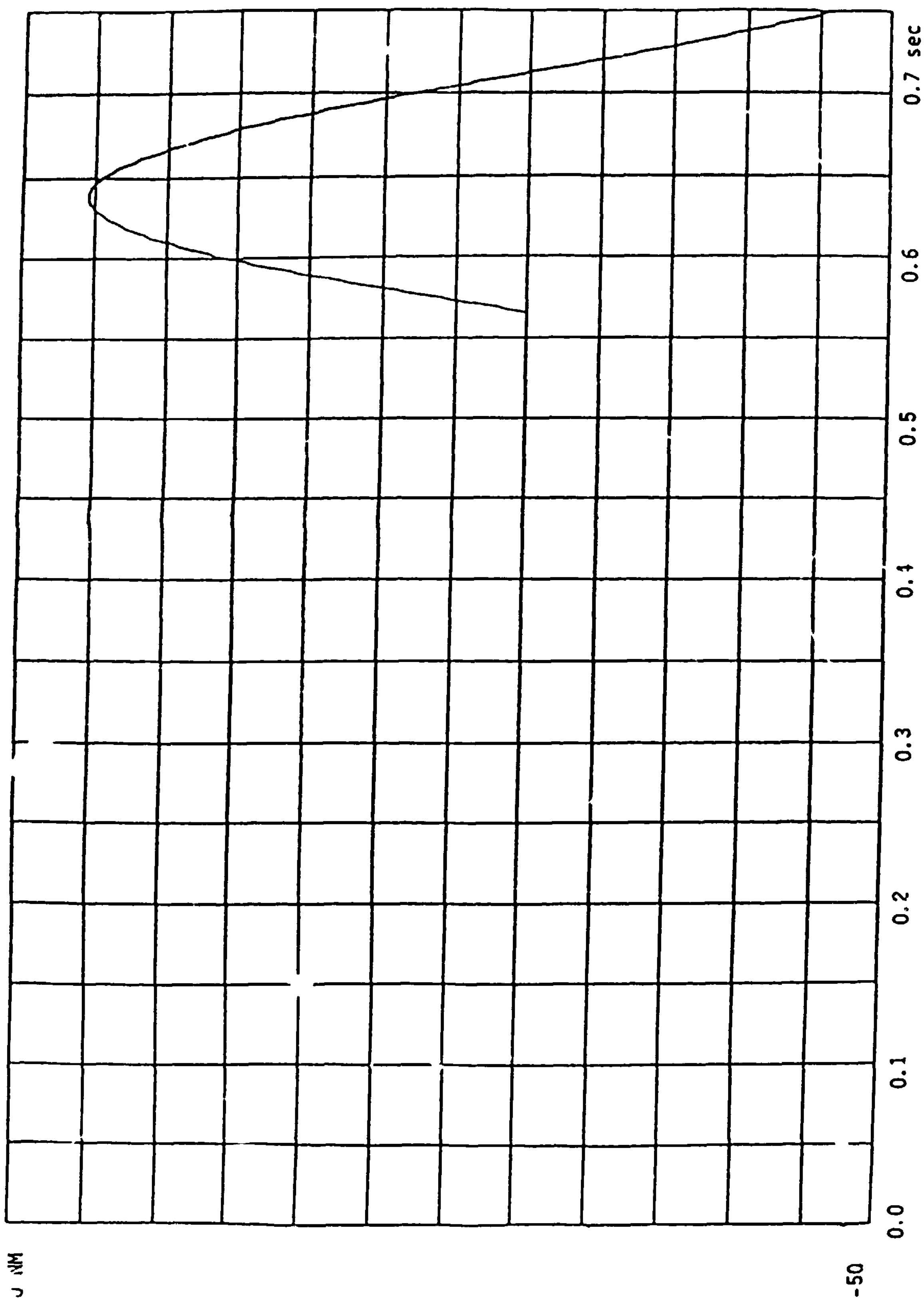

Figure 8. Constraint Torque Normal to Deployment Plane

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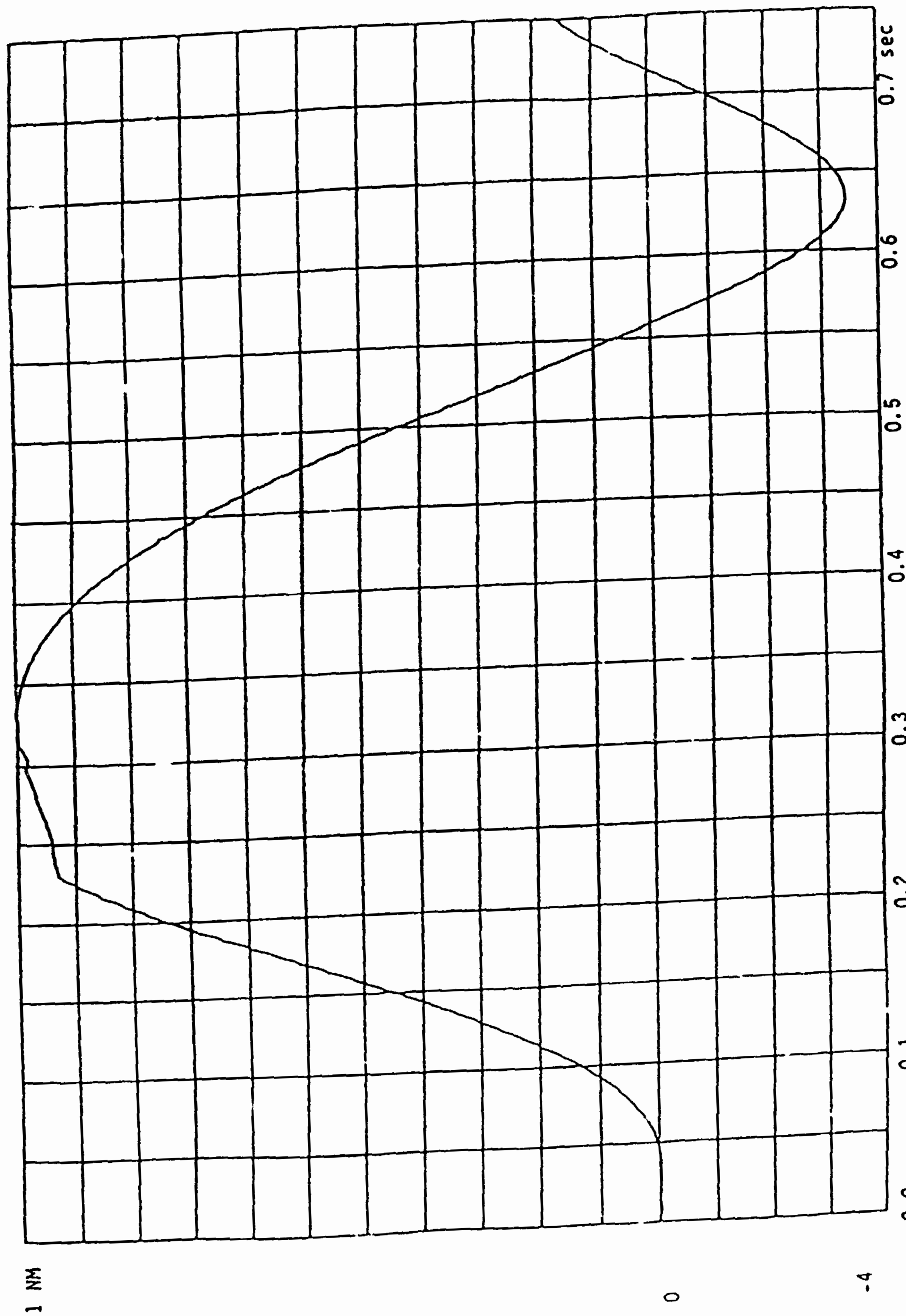

Figure 9. Constraint Torque in Deployment Plane